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UNIVERSAL WEAVING FOR TURBINE ENGINE COMPOSITE COMPONENTS

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3-D weaving/braiding technology being pursued at ITAC has the potential to result in techniques for manufacturing low cost, high volume, near net shape, multiaxially reinforced (through the thickness) fibrous preforms, utilizing a cartesian weaving/braiding plane, for high temperature composite applications. These techniques lend themselves to the manufacture of hybrid preforms; fiber assemblies that contain more than one shape or fiber architecture. With this tool, designers may optimize the fiber structure and shape of a preform along the length of composite parts to maximize performance. A low cost hand loom has been designed and built to demonstrate concepts empirical to this technology, laying the ground work for a fully automated 3-D cartesian weaving machine.

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PROJECT SUMMARY

The purpose of SBIR program "Universal Weaving for Turbine Engine Composite Preforms" was two fold:

1.) Demonstrate the feasibility of using miniature weaving machine components to reduce the cost and automate the process of manufacturing near net shape preforms.

2.) Demonstrate shaping, joining, and hybrid fiber architecture capabilities offered by 3-D cartesian weaving/braiding technology.

During this program we have designed and built a relatively low cost 3-D cartesian hand loom capable of handling up to 4000 weaving/braiding elements (4000 longitudinal strands). The elements have been fabricated using plastic injection molding, and the cost of producing each individual weaving element is approximately $.10 per element. In the course of building this apparatus we have identified certain design criteria necessary to build a fully automated 3-D preform fabrication machine. Several preforms were also fabricated including a 3-D braided ring with fibers oriented predominantly in the radial direction, as well as a conceptual turbine blade with a thick root section and a transition to a thinner blade section.

Cartesian 3-D weaving allows the manufacture of relatively thick fibrous preforms with flexible fiber architecture, shaping capability, and high fiber volumes. Equipment for the equipment of preforms for volume applications may be produced cost effectively in several ways:

1.) Make several low cost hand assisted weaving looms which are extremely flexible to set up for prototype validation and moderate preform production quantities. These looms are capable of weaving from 1" to 3" per hour depending on the complexity of the fiber architecture. Resultant preforms would be moderately priced, but ramping up to meet volume requirements is relatively inexpensive. It would be possible to set up an array of these hand looms between $5,000 - $10,000 each.

2.) Build fully automated equipment. After the design for a component has been validated, it may be desirable to increase production rates. This may be achieved by building automated equipment. It will be relatively expensive to build such equipment because it will involve close tolerance manufacture of mechanical components, additional automation systems not required in manual equipment, and machinery will be moderately specific to a particular preform. When designing a family of automated equipment it is possible to standardize many of the parts to minimize the cost of reconfiguration.

Both of these options are made possible through the concept of miniature weaving/braiding elements, elements which approach the size of the final preform in one dimension. The elements would be analogous to the needle of a sewing machine or the latch needle of a knitting machine whose cross section approaches the size of the yarns (fiber bundles) they are working with. There will obviously never be a single preform formation system that will be able to meet all the application requirements posed by advanced composites, but for solid structures with cross sections smaller than 6" x 6" it is necessary to apply this miniature weaving element system if high volume low cost fibrous preforms with high fiber volumes are ever to be produced automatically.

Applications for this technology are present throughout the composites industry. Applications for turbine engine components include preforms in refractory matrix (carbon-carbon, and ceramic matrix) composite applications such as turbine blades, rotating rings, actuators close to the engine core, and support structures. Other applications include organic composites which will tolerate some reduction of in-plane properties for greatly improved damage tolerance and fracture toughness.

TABLE OF CONTENTS

INTRODUCTION

Tremendous strides have been made in turbine engine performance since their introduction in the early 1940's. The USAF, DoD and NASA have recently introduced a program whose goal is to increase the thrust-to-weight ratios of aircraft turbine engines to 20:1, double that of current military engines, by the end of the century. In order to achieve the goals of IHPTET (Integrated High Performance Turbine Engine Technology Initiative), it will be necessary to develop materials, that allow engines to burn hotter for more efficient combustion, weigh less, and are able to be formed into more efficient parts to reduce the overall part count.

Materials which have gotten us to this point - titanium, superalloys, and advanced polymer composites - will not meet the temperature requirements of the next generation turbine engines. Projections are that in order to meet the goals posed by IHPTET, air reaching the compressor - the first hot stage - will already be at 900°F, the temperature will rise to 1800°F inside the compressor, then rise to 4000°F in the combustor. Current nickel based superalloy hot sections operate at 1800°F (within 200°F of their melting point), not capable to reach the IHPTET target temperatures.

Ceramics and intermetallics such as the titanium aluminides are materials which may approach the necessary operating temperatures, but have been avoided by engineers in the past because of the brittle nature of these materials. Fibrous reinforcement of these materials improve their toughness and make them candidates for turbine engine components. These reinforced materials will not only allow higher operating temperatures, but may also allow engine manufacturers to reduce or eliminate cooling systems, allowing lighter weight turbines with simpler parts. [1]

Fracture toughness and delamination resistance are significantly improved in brittle materials through the use of fibrous reinforcement. The directional properties of fibers allow the efficient design of high strength high stiffness components. To assure damage tolerance in aerostructures subject to complex loading such as turbine engine components, it is necessary to eliminate non-reinforced planes within structures. Elimination of these planes can be accomplished through the use of 3-dimensionally oriented reinforcement. 3-D reinforcement may be provided by low-aspect particulate or whiskers, but continuous fiber 3-D reinforcements show significant structural advantages. Fibrous reinforcement structures should also be near net shape because the cost of machining these tough brittle materials is so high that they would be economically unfeasible.

ITAC has addressed techniques to form near net shaped fibrous preforms during this SBIR program. These techniques are versatile not only in shaping 3-D preforms, but they also allow a great deal of freedom in choosing fiber architecture best suited to the application. Joining techniques allow several preforms to be

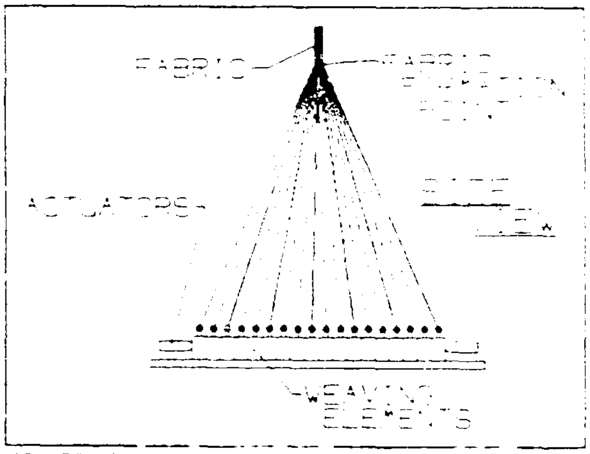
combined with other preforms or fabrics to eliminate fasteners and possibly reduce the number of parts. There is still a great deal of work to be done to develop thermally stable, oxidation resistant, high temperature fibers, matrix materials and coatings. We are concurrently developing the weaving technology that will maximize the performance of these new fiber/matrix composite systems.

MARFS TECHNOLOGY

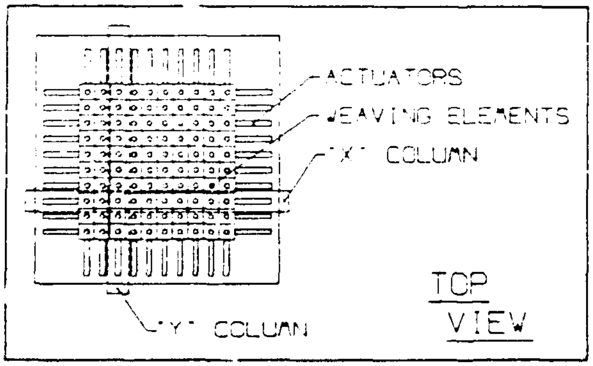
ITAC has developed a technique for fabricating Multi-Axially Reinforced Fibrous Structures (MARFS) or 3-D fabrics on a cartesian weaving system. Using this technique it is possible to produce MARFS with a wide range of fiber architectures including 3-D braids orthogonally woven (X,Y,Z) structures, and other quasi-isotropic structures. Several fiber architectures may be incorporated into a single hybrid structure, allowing engineers the freedom to optimize designs by tailoring the fiber orientation along the length of a preform. Cross-sectional geometry is defined by the weaving array, and shaping is readily accomplished by ply drop-offs and fiber architecture manipulation and transition. Joining techniques have also been developed which allow basic structures to be combined into more complex structures such as rings and trusses.

FIBER ARCHITECTURE

ITAC's weaving technique is based on manipulation of a Cartesian weaving grid. In a Cartesian weaving grid, rectangular elements are set out in a grid similar to the squares on a piece of graph paper. Warp tows (0° or "Z" direction) are perpendicular to the weaving plane and extend to the fabric formation point.



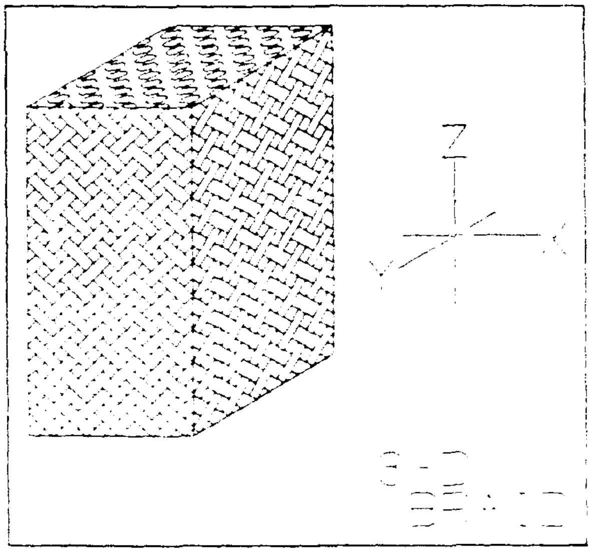
CARTESIAN WEAVING LOOM



Actuators on all 4 sides of the grid control the individual columns of elements which may be moved in the X and Y directions. By manipulating these elements and selectively placing filling yarns, it is possible to form a wide array of fiber architectures.

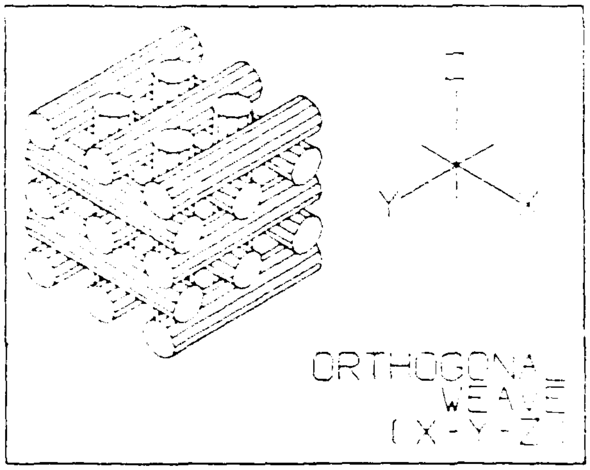
1. 3-D Braids

3-D braids are solid structures with all tows oriented between 15° and 40° with respect to the longitudinal axis. Interlacings are formed when adjacent columns of weaving elements are transposed in opposite directions; first all X columns, then all Y columns.(A 1x1 braid would denote that both the X and Y columns were transposed by 1 weaving element. The 3-D braid orientation will minimize delamination because of interlacings crossing through all planes. Properties will be primarily longitudinal. Additional 0° fiber may be included in the structure by braiding around these unidirectional tows so that the fiber orientation approaches 0°/± braid angle in all planes. 3-D braids can result in parts with relatively high fiber volumes in excess of 60%. When the preform is debulked, the individual tows pack together without buckling through the "Chinese finger handcuff" effect (tows jam against each other). As a result, the debulked preform will have lower fiber angle and slightly longer length.

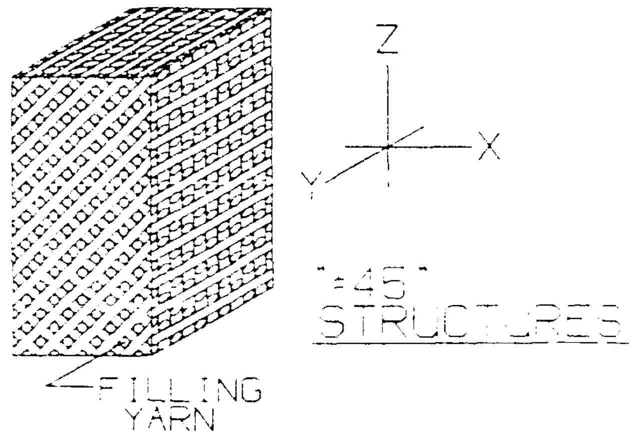


2. Orthogonal X-Y-Z

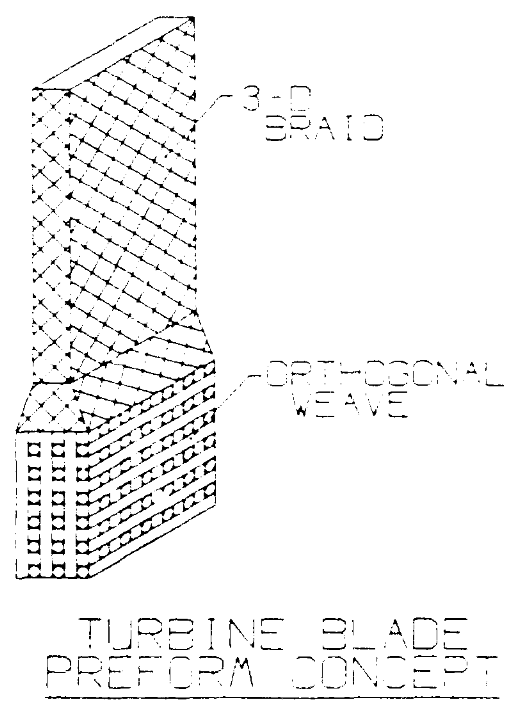
Orthogonally woven structures are formed when filling yarns are placed between the rows and columns of 0° or "Z" direction tows. The volume fraction in each of the 3 directions can be controlled by the tow size used, and it is in this way that the mechanical properties of the part can be adjusted. The practical fiber volume limits of orthogonal structures is between 45-50%. Preforms are woven to the net shape of the final part. De-bulking after preform fabrication would deteriorate mechanical properties because the individual tows, which are straight in all directions, would buckle under pressure.



3. (±45°) Structures Structures with a ± orientation with respect to one of the longitudinal planes may be formed by moving the elements of the weaving plane in one direction only (either the X or Y), and securing the interlacings with a filling yarn. This architecture will yield a preform with excellent shear resistance. Additional variations of this structure include 0° tows inserted between the ±45° "columns". This preform would have a 0/±45°-90°(through thickness) orientation with almost isotropic properties.



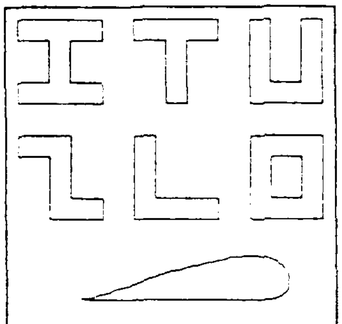
4. Hybrid Structures MARFS technology allows several fiber architectures to be combined in a single preform structure. The advantage of hybrid 3-D preforms is that they allow designers to choose the optimum fiber orientation for each section of a composite structure. For example, if you were designing a fastener, it would be possible to put additional 90° fiber in the head to distribute head loads, transitioning to a longitudinal orientation (3-D Braid) in the shank to carry the tension loads. A turbine blade preform could have an orthogonally woven root section changing to a thinner 0/±45° or 3-D braided architecture in the blade. As long as the part's geometry fits within the limitations of the weaving grid, fiber architecture is flexible and can be customized for optimal composite performance. Several types of fiber may be included in a single preform. Other types of components such as tubes, wires, sensors or fasteners may also be woven into these MARFS.



Fiber Architecture Summary: Using ITAC's MARFS fabrication technique, the fiber architecture in a 3-D preform can be tailored to suit specific application requirements. Fiber tows lie straight within these structures and contain no crimp with the exception of small amounts in 3-D braids. This insures higher translational efficiencies than with conventional 2-D "textile" materials.

PREFORM GEOMETRY and SHAPING

This weaving/braiding technique offers considerable shaping capability both in cross-section and longitudinally. Cross-sections include rectilinear shapes such as T-I-J-L, and more complex shapes such as hollow squares and airfoil sections may also be woven.


CROSS-SECTIONAL SHAPES

Cross-sectional shape can be changed along the length of the preform to change it's longitudinal profile. This is accomplished using several techniques:

1.) The most obvious way to change shape is by selectively adding or subtracting tows to the structure.

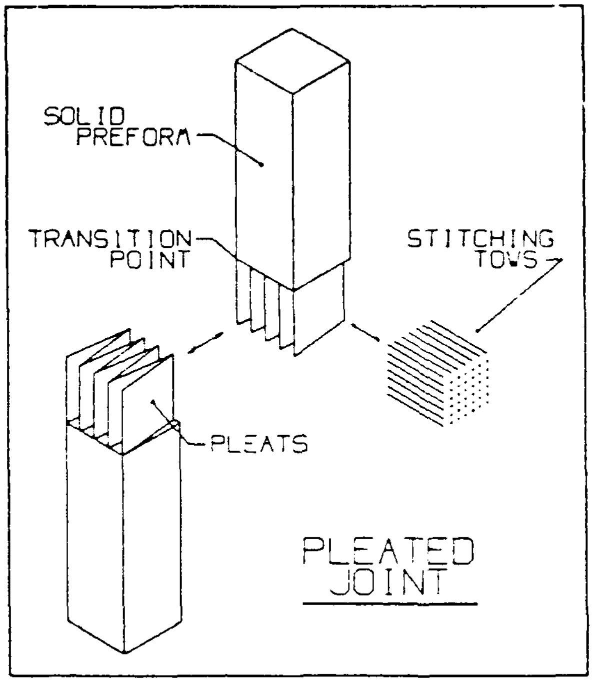
2.) Weaving grid may be rearranged during fabrication. For example a square could transition into an I section.

3.) Through Fiber architecture selection it is possible to change cross-sectional shape. For example by changing the architecture of a square array 3-D braid from a 1x1 to a 1x2 construction, the preform changes from a square to a rectangle. A 1x2 to a 2x1 braid construction will yield a rectangular preform that is offset by a 90° rotation at the transition. A transition from an orthogonal weave to a 3-D braid will result in a thinner cross-section, and a change in architecture from a mostly isotropic structure (X-Y-Z weave) to a more directional structure (3-D braid).

By combining the above techniques with bending the resin-free preform to accommodate curves or bends in the mold/tooling it is possible to achieve a wide range of preform geometry with ITAC MARFS technology.

JOINTS

ITAC has developed a technique which allows MARFS to be jointed using a 3-D reinforced joint. The solid preform is divided into a series of pleats at a transition point. This pleated section can be at an end or in the middle of a preform that is to receive a joint. A joint is formed when the pleats (or divisions) of one structure are positioned between the pleats of a second structure. Third dimension reinforcement is added to the joint when additional tow is stitched through the joint perpendicular to the pleated plane. The joint is a 3-D orthogonal structure made from portions of the two preforms being joined.

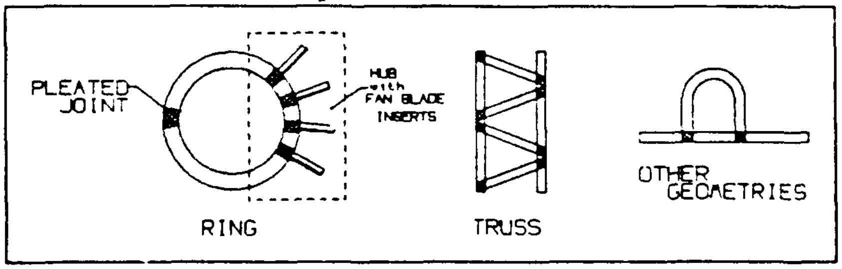


Using this technique it is possible to form:

1.) Ring Structures: A solid length preform is woven with pleats at either end. The preform is bent and shaped into a ring, the pleats passed through each other, and the joint secured with stitching.

2.) TRUSS ASSEMBLIES: Trusses or other complex structures may be formed by jointing lengths of preforms into the desired configuration.

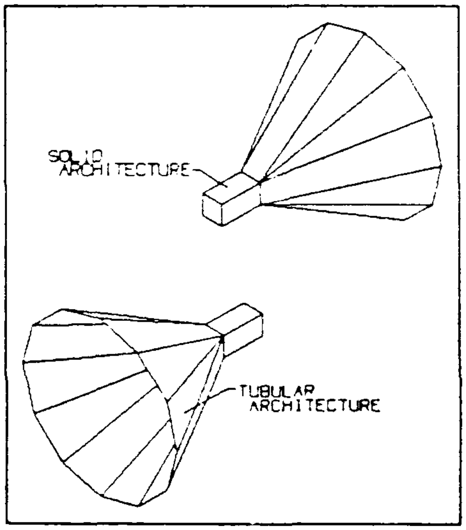
3.) INTEGRAL HUB/FAN BLADE ASSEMBLY: An integral rotor can be formed by joining blade elements to pleated sites located around the circumference of a ring structure.

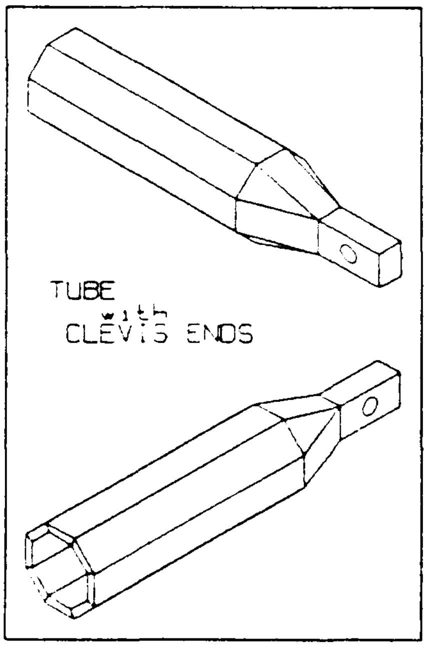


3-D MARFS/ 2-D BRAID HYBRID STRUCTURES

ITAC has recently consolidated its efforts with the Western Filament organization (also a small business). As a result, there have been additional fiber architectures involving hybrids of 3-D MARFS and 2-D Braids which have been identified. Western Filament is an industrial braiding company with extensive experience in handling both conventional textile fibers as well as advanced fibers such as Kevlar®, ceramic, and carbon for composite applications.

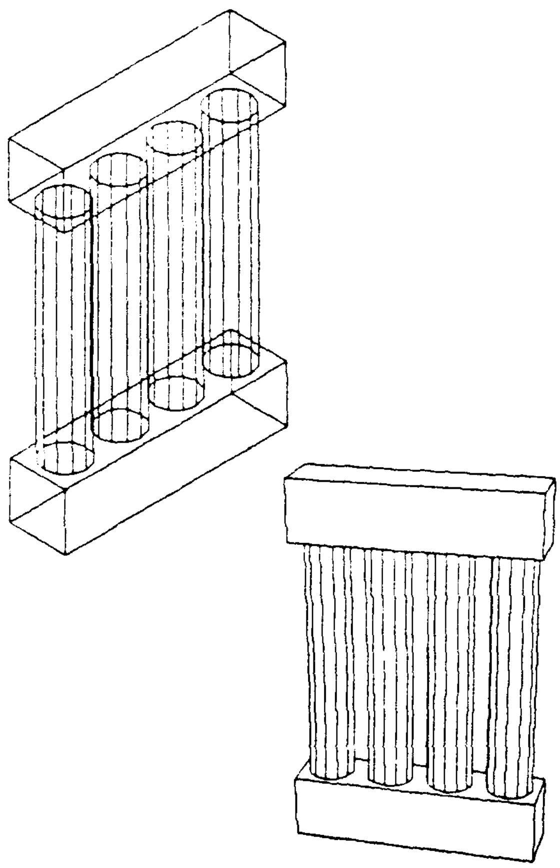
Hybrids of 2-D and 3-D braid are formed when part of a structure is woven on a 3-D machine, and the remainder is formed with a conventional braiding device. One of the simplest structures that can be created using this technique is a cone structure with a solid throat and a 2-D braided skirt section. One application for this type of a structure is a small rocket nozzle. The fiber architecture in the throat is designed to best support the attachment point, the skirt which is primarily an ablative surface is the 2-D braid.





2-D braided structures have long been used for tubular structures because they are continuous around the circumference, the resultant fiber structure is naturally balanced (the positive and negative angles of the braid are always the same with respect to the axis, as long as the part is symmetric around the axis), and braid will accommodate changes in cross section. One of the challenges facing braided tubes is that the ends cannot be closed, requiring that end fittings or caps be used. Combining MARFS and 2-D braids enables the end (a clevis or other structure) to be fabricated in a 3-D architecture, continuing with 2-D braid for the barrel of the tube. In this way it is possible to combine both the tube and the fitting in a single structure without a secondary bonding or fastening procedure.

One of the most complex structures that may be created using this hybrid 2-D/3-D technique is a "Manifold" structure. This is a fibrous assembly that starts with a 3-D block architecture, has several parallel tubes braided that transition from the block, then transition once again to a block structure. The block structures at either end of the manifold may either be formed around a tube, or the port to the manifold may be cut into the block after consolidation. Applications for this type of a structure may include high temperature heat exchangers, stiffening structure, or perhaps pipe fittings and joints.

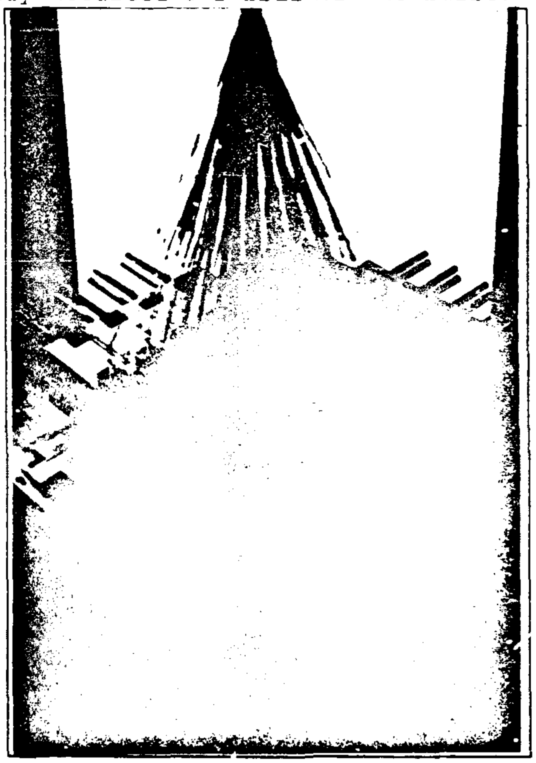


MANIFOLD

3-D SUSPENDED RAIL MANUALLY ASSISTED WEAVER/BRAIDER

Background:

In November of 1989, Konrad Krauland the principal investigator on this program, received patent #4,881,444 "Method and Apparatus for Braiding 3-D Fabrics". This patent outlines the systems and motions necessary for automatic 3-D braiding including the miniature braiding element concept and automatic compaction of interlacings with a reciprocating comb. It very quickly became clear that building an automatic machine is a complex, expensive, long term project, so a manually assisted 3-D braider was built.

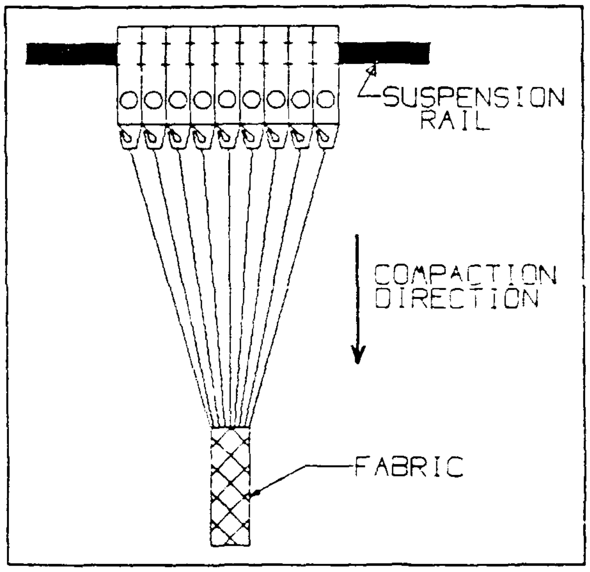


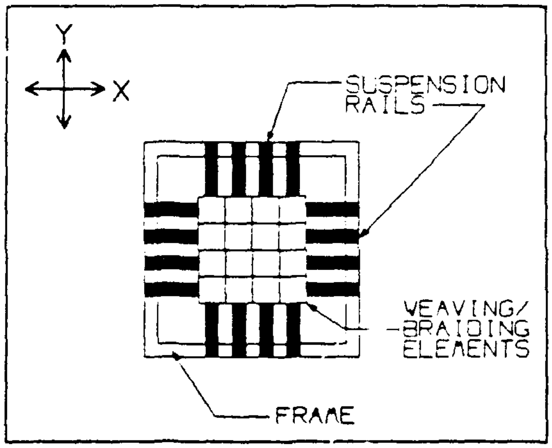
This first 3-D braider has only 99 elements arranged in a 10 x 10 braiding array, not nearly large enough to make fabrics of significant size. When using a single end of 12K carbon tow, the resultant fabric is only about 3/8" by 3/8" square in cross-section. This device is similar to other conventional 3-D braiders in that weaving elements with hooks travel about a relatively large weaving plane. Fiber bundles with an elastic tensioning device are attached to a fixed point above the braiding plane. Interlacings are formed when the columns and rows are transposed. These interlacings are then lifted (or beat-up) to the braiding point to form the fabric. Several refractory matrix composite manufacturers I visited with advised that data shows that finer weave patterns result in composites with better translational properties than coarse weave patterns. The new goal then became to produce an easily reconfigured manual 3-D braiding loom capable of handling a larger number of fiber bundles which was easier to build and less expensive than the first 10 x 10 braider.

It was in trying to reach this goal that the concept of the miniature element manual weaver/braider was conceived. The thinking was that if we could use miniature elements for an automatic 3-D braider, why not use lower cost miniature weaving elements to build a manually assisted loom. I then built the first prototype Suspended Rail 3-D weaver/braider.

Weaving/Braiding on a 3-D Suspended Rail Loom

Weaving on a 3-D Suspended Rail Weaver/Braider (SRWB) is significantly different from braiding on a conventional 3-D braider. With a SRWB, the weaving elements are positioned at the top of the device with the fiber tows extending downward. Interlacings are compacted downward; the fabric is formed from the bottom up instead of from the top down, Which utilizes the aid of gravity in the fabric formation process. It has been my experience that when compacting upward, the interlacings tend to loosen up after compaction due to the pull of gravity combined with the pull of the elastic tensioning member. When compacting downward, the interlacings stay in place after beat-up allowing you to weave a denser preform with higher fiber volume, and a finer weave/braid pattern.

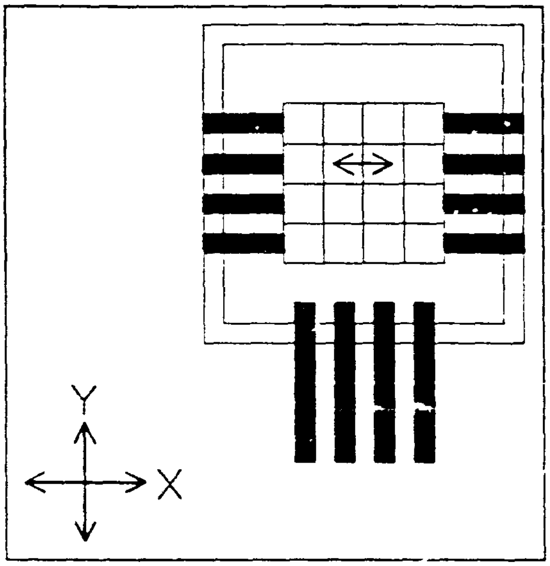




Each of the elements in an SRWB is relatively small in cross section, approximately 1/4" x 1/4". Two sets of suspension rails, one going in the X direction, the other in the Y direction, pass through the weaving elements and rest on a frame. These suspension rails support the weaving elements above the preform.

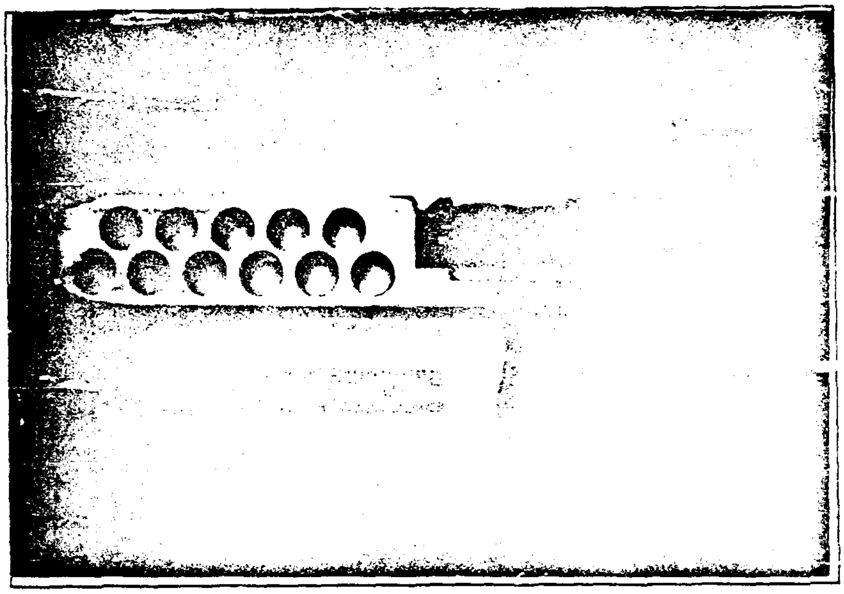
3-D braiding motions are accomplished in the following way:

By removing the Y direction suspension rails from the cartesian weaving array, only the X direction rails remain to support the weaving elements. At this point, the weaving elements are free to move in either direction along the X rails. The Y suspension rails are reinserted after the element transposition in the X direction is complete. The X direction rails may now be removed so that the Y direction element transposition may take place. By alternating X and Y element transpositions in this way, interlacings basic to the 3-D braiding process are being formed.



After an interlacing has been formed, it is necessary to compact or beat-up the interlacing to the edge or fell of the preform. This is accomplished manually using a smooth rod to push the interlacings downward. Both the X and Y suspension rails are left in place during this procedure. If you are first compacting between the X direction rails, you begin by moving the first rail one or two inches in the Y direction away from the rest of the weaving array to create a space into which the compaction rod may be inserted. After beating up the first row, the second X rail is moved next to the first one so that the "beat-up gap" now exists between the second and third row of elements. This procedure is repeated, one row at a time, until the interlacings have been compacted between all the rows. After completing the X direction rows, it may be desirable to compact the Y direction rows.

Orthogonal X-Y-Z fabrics are formed when filling yarns are inserted between the longitudinal warp tows. These filling or transverse yarns may be inserted using a shuttle (see photograph of shuttle on the top of the next page). The shuttle is passed through the space created when two adjacent rows of weaving elements are separated (instead of the compaction rod) to insert a filling yarn. By inserting filling yarns first between all of the X rows, then all of the Y rows (repeat, repeat, repeat,...), an orthogonal fabric is formed. By combining filling yarns with transpositions of weaving elements as in 3-D braiding it is possible to form a wide variety of fiber architectures as outlined in the previous section on fiber architecture.



Advantages of SRWB Technology

There are many advantages to using this SRWB technology for the fabrication of prototype components or small production requirements:

1.) Smaller weaving/braiding plane

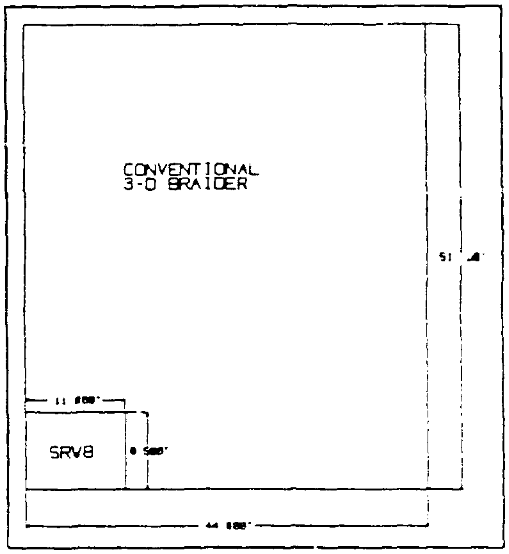
2.) Easily reconfigured

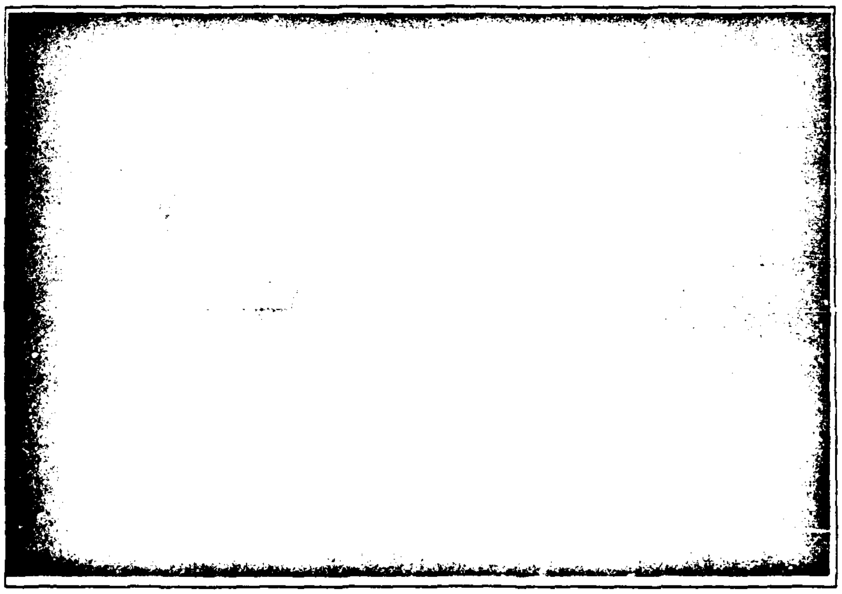
3.) Less expensive to build

4.) Less material waste

5.) Better weave consistency throughout the preform

1. A smaller weaving plane is much easier to handle than a large plane. It is easy to see the movement of the yarns through the structure. Operating the device in a smaller area is also more convenient and takes less force by the operator. If you were to set up a cartesian weaving grid using the miniature components, that is as big as the sheet of paper this report is printed on (8 1/2"x11") using the weaving elements molded for this SBIR program (1/4 in^2), this array would contain 34 x 44 weaving elements or a total of 1496. If we assume that with conventional 3-D braiding equipment the smallest cell that a braiding element can fit into is 1 1/2" long by 1" wide, then a conventional 3-D braider containing 34 X 44 elements would be at least 51" x 41".



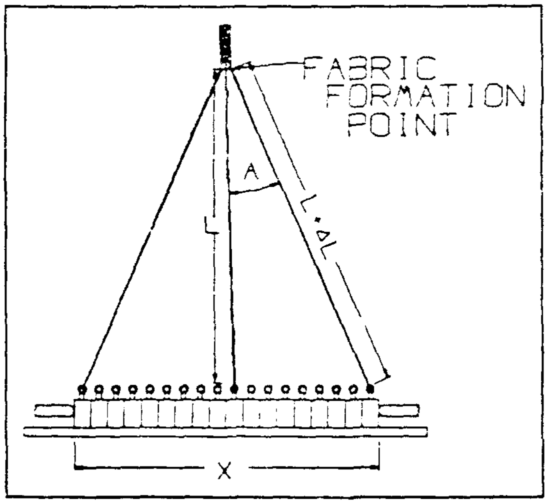


The photograph at the left shows a SRWB rail with 24 elements. As you can see all 24 of these elements measure a mere 6" in length.

2. A SRWB is easily reconfigured. It is possible to weave with either a very small number of suspension rails in each direction, or a large number of rails, up to the capacity of the weaving frame. The shape of the cartesian array set out on the rails will determine the cross sectional shape of the preform. (These cross sectional shapes were discussed in an earlier section on Preform Geometry and Shaping.)

3. Depending on the fabrication method used to form the weaving elements, a SRWB device can be built at much lower cost than a conventional 3-D braider. Since the weaving elements built for this program were injection molded, the cost of each weaving element is relatively low (less than $.10/element). The greatest cost associated with a loom is the suspension frame. The cost to build suspension frames would be reduced greatly if the need to build a battery of these frames becomes apparent.

4. Less material waste. During 3-D braiding or preform formation, weaving/braiding elements migrate from the edge of the braiding plane to center, then back to the edge. The distance from the braiding plane to the fabric formation point is L when the element is at the center of the plane and L+ΔL when the element reaches the edge of the weaving/braiding plane. This ΔL is compensated for through the use of an elastic member suspended between the end of the tow and the braiding element. Angle A and ΔL is a function of both L and X (the size of the weaving/braiding plane). As the preform is braided or woven, the fabric formation point comes closer and closer to the weaving/braiding plane, decreasing L and increasing both ΔL and angle A. At some critical point, ΔL and A become so large that braiding is no longer possible. It is at this point that preform fabrication must stop, and any material left between the fabric formation point and the weaving/braiding plane becomes waste. The smaller the weaving plane X, the shorter will be length L when A reaches the critical point. This waste may be insignificant when working with relatively low cost carbon yarns, but will certainly influence cost when working with extremely expensive advanced fibers.



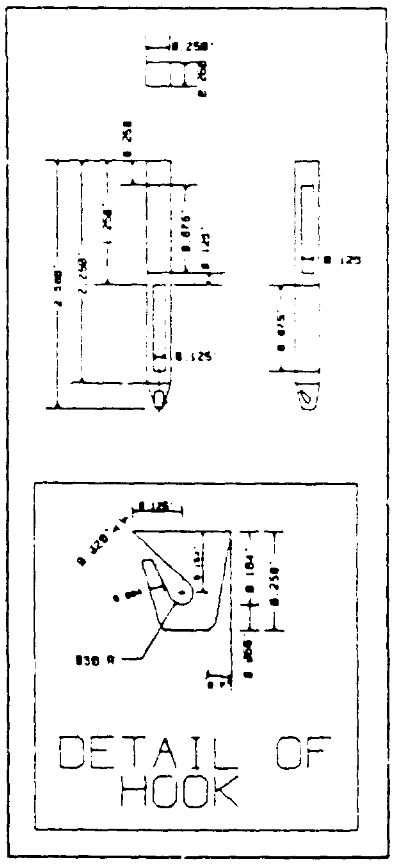
5. A smaller weaving plane also improves the consistency of the weave throughout the preform. Referring to the diagram on the preceding page again, it has been my experience through working with the 10 x 10 braider (1st photograph), that as a fabric is formed and A becomes larger, it is necessary to compact harder to achieve the same weave density as when A is smaller. This is due to the outward component of the tension force applied by the elastic member - some tension is necessary to keep the tows straight during braiding/weaving. This outward tension component increases as A increases, and causes the weaving pattern to become less dense because interlacings start to slip back towards the weaving plane. Decreasing the size of the weaving/braiding plane minimizes this effect.

A disadvantage with using a SRWB is that there is some extra motion involved in the weaving process, the removal and insertion of suspension rails during braiding, which will slow the braiding process down a little bit.

DESIGN CONSIDERATIONS AND CONSTRUCTION OF THE 3-D SRWB

Suspension Rails

The primary design consideration with this manually assisted weaving/braiding device was the shape and size of the suspension rails. In the first prototype SRWB built, suspension rods with a circular cross section were used. Rods were chosen for the prototype unit because it was easy to drill holes into the metal weaving elements, and I was able to fabricate the complete device in-house. Prior to building this device there were concerns about bowing of the rods as tension is applied to the yarns during weaving which would cause misalignment of the elements. This in fact did occur during weaving, and a stiffer suspension rail would need to be selected for larger weaving arrays. (The prototype SRWB held up to a maximum of 250 weaving/braiding elements.) Suspension rails with a rectangular cross section measuring 1/8" thick by 7/8" high were chosen because they provide many times the stiffness of the original rods, and they allowed us to produce weaving elements with sufficient wall thickness maintaining the target cross sectional dimension of 1/4 in^2. With the dimension of the suspension rail chosen we set out to build a weaving/braiding loom capable of handling arrays as large as 80 elements by 50 elements, or a total of 4000 elements. (4000 individual tows in the structure)



Weaving/Braiding Elements

The next step towards building this SRWB was to design the weaving elements, and choose a cost effective manufacturing process to built them. The weaving element designed for this application appears in the figure on the right. These weaving elements were designed to accommodate suspension rails which pass through both longitudinal surfaces of the element. The hook of the element holds the elastic member attached to the reinforcement tow. The space between the tip of the hook and the body of the element is narrow so that you have to stretch the elastic a bit to reduce the diameter enough to fit into this space. This prevents the elastic from accidentally slipping out of the head of the hook during weaving or if one of the tows breaks.

Several processes to fabricate these weaving components were evaluated:

1. EDM - Electro Discharge Machining
2. PMP - Powdered Metal Parts
3. Plastic Injection Molding

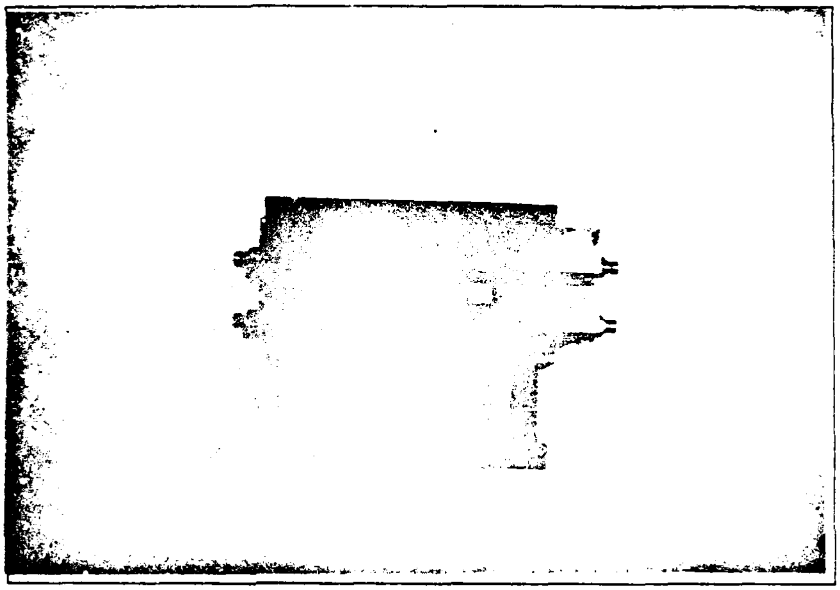
1. Wire EDM would have been the best way to fabricate these components if we would have been making a small number of parts. With wire EDM, a positively charged wire is held against a negatively charged metallic workpiece. As the wire comes in contact with the workpiece there is electrical discharge which burns through the metal, cutting the part. Very close tolerances are possible using this method of machining, and programming the equipment is relatively simple with a CAD/CAM system. Cutting rates are low, up to 1"/minute depending on the thickness of the workpiece and the thickness of the wire being used. Using this method of machining the parts would have cost about $15 - $20 per part on volumes of 500 to 1000 parts. If an automated 3-D weaver/braider is built, wire EDM will be the method of choice to produce close tolerance elements for the floating former plate.

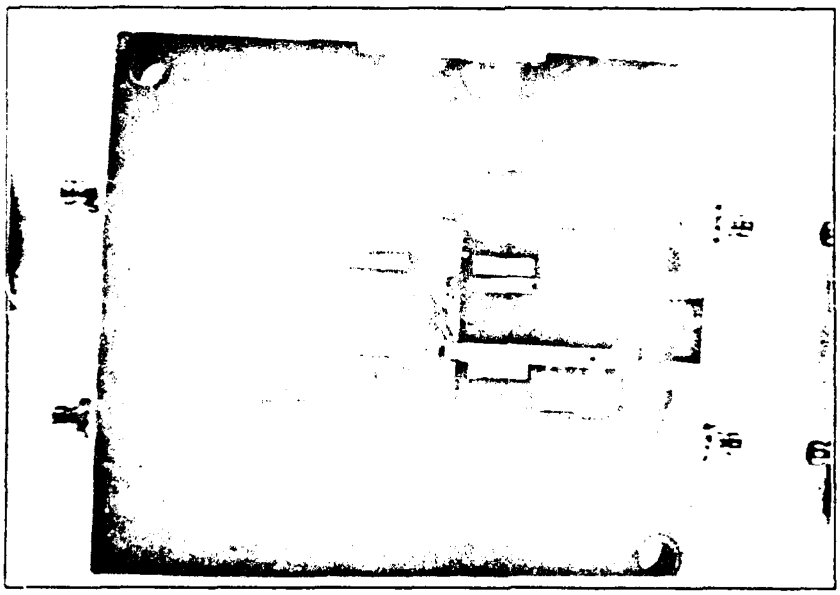
2. Powdered metal parts are made when very fine metal powder is compressed into a mold cavity under high pressure. When the part is ejected from the mold, it has the general shape of the final component, but is very brittle because the metal powder is not bonded. After the compression molding operation, the parts are sintered in a high temperature oven. During sintering, the temperature of the oven is set at the point that the metal powder starts to soften. The outer surfaces of the metal powder particles bond to each other and form a virtually solid part. There is a small amount of shrinkage that occurs during sintering which is taken into account when designing and building the mold. With powdered metal parts, it is possible to form a hole in only one direction - the transverse cavity to fit the second suspension rail would have had to be formed in a secondary broaching operation. The cost of producing the initial part, that is the part without the second broached slot, would have been in the $1.00 - $1.50 range. Tooling for PMP is very expensive because of the abrasive nature of the powdered metal. Tolerances are not as close as with wire EDM. It is interesting to note that many components for sidearms and rifles are made using PMP technology.

3. Plastic injection molding was chosen because the cost per part was extremely low, tooling costs are reasonable, and the weight of the finished part is much lower than with metal (this allows our rails to hold more weaving elements). Tolerances are not as close as with either of the above methods, but I felt that ±.002" would be close enough for this application. A tough nylon resin was chosen which would be able to withstand the in and out movement of the suspension rails. Furthermore, it is possible to dye the nylon parts different colors. Parts of different colors are used as an aid in the weaving of complex preforms to help differentiate the motion of various systems of fiber bundles.

Fabrication of the injection mold and molding of the elements was contracted to SCI Precision Molds of Fullerton CA. A four cavity injection mold was built for our weaving elements. This mold is capable of producing over a million parts in its service life.

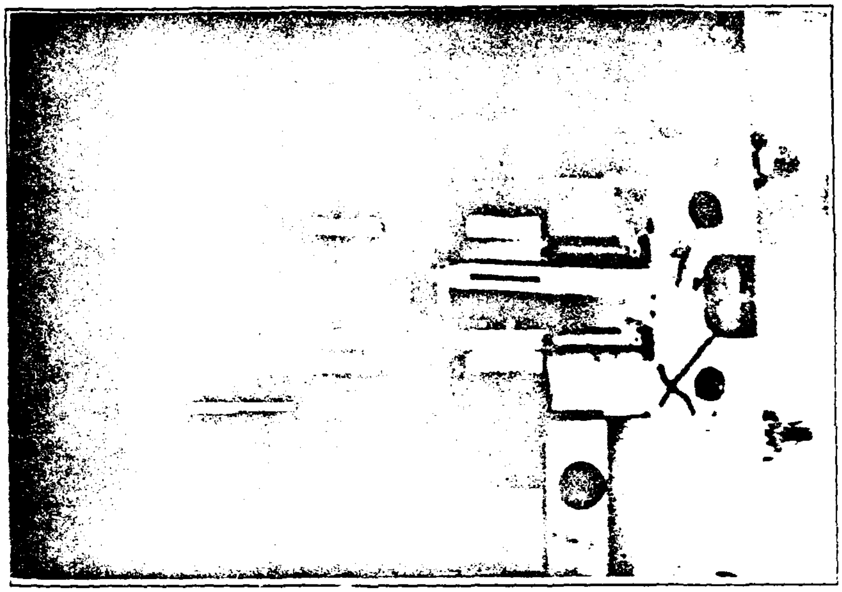
The series of pins situated below the mold are ejector pins used to push the finished parts out of the mold after the plastic has been injected.





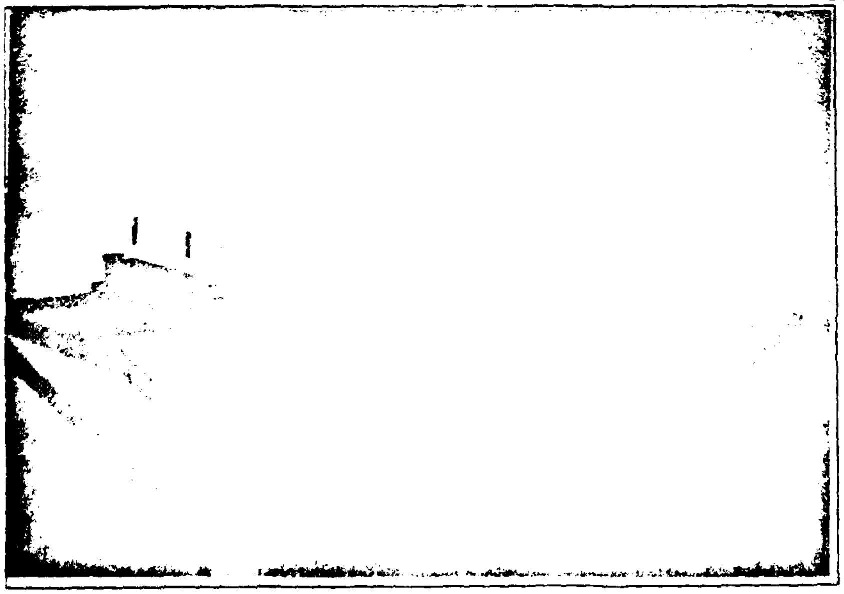
The photograph on the left shows the open base of the mold with its 4 cavities. The lower right hand cavity has an element in it. The three small holes down the centerline of each cavity are for the ejector pins which push the part out of the mold after the molding cycle is complete.

The suspension rail holes going through the weaving elements are molded into both longitudinal sides of the elements, so it was necessary to build a complex mold with sliders. The posts at the back end of the part (parallel with the ejector pins) form the hole



or slot at the rear of the element. In order to mold the forward slot into the element, it was necessary to include a sliding post into the mold. The sliding posts (1) are attached to pusher bar (2). Before a molding cycle, the mold is closed, and a cam attached to the mold base automatically pushes these posts into position. The nylon is then injected into the cavity, and a cooling cycle begins. When the part is cold enough to be removed from the mold, the mold opens, and the spring loaded sliding posts retract. The ejector pins then push the part out of the cavity into the part bin located below the injection machine. If these posts were not removable, it would be impossible to remove the parts from the mold.

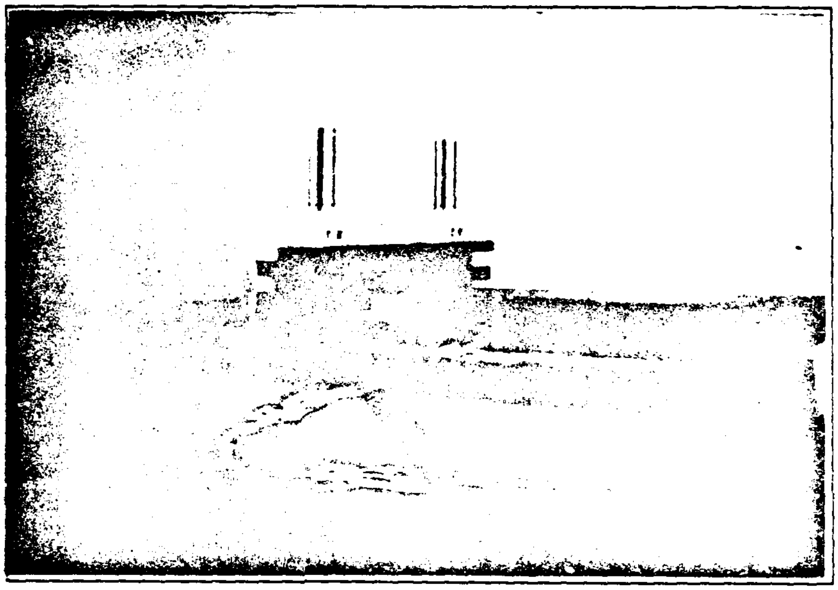
Weaving/Braiding Frame

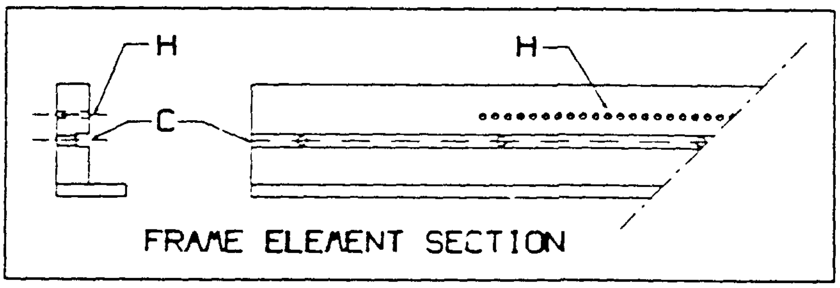


The frame for this weaver/braider was designed to maximize the efficiency of the operator. This photo shows the frame and its primary features. The package of carbon yarn on the frame is for scale. The frame sits 60" high, and

depending on the size of the array and the fiber architecture, parts as long as 48" can be fabricated on this device. The core or center square of the frame where the weaving elements are located measures 2C" wide by 36" long.

Suspension bar removal carriages with air cylinders mounted on top are located on two sides of the frame. These carriages which run on ball bearings slide on the outrigger rails located beneath the removal carriages. When the rails are to be removed, the air cylinders are actuated, and hold onto the suspension rails. The suspension rails are removed as the carriage slides backwards. When the X direction rails are removed, the elements may be transposed along the Y direction and vice versa.



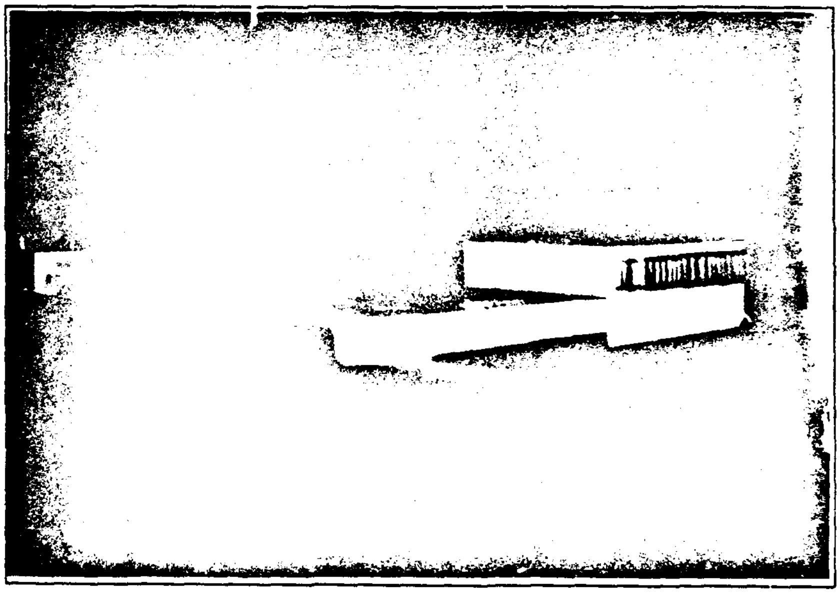


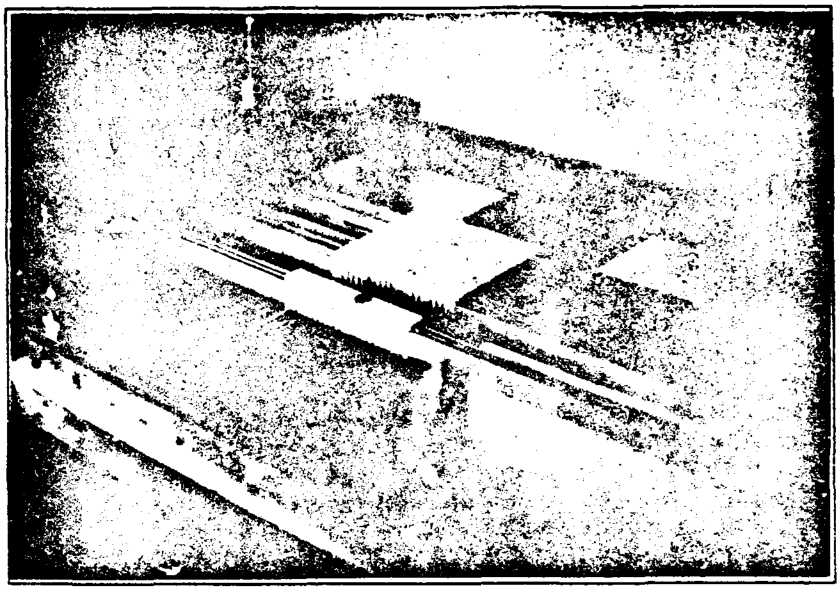
The drawing to the left shows additional features which have been designed into the frame elements of this machine. The holes (H) in the frame are for pins which are used as suspension rail spacers and guides. These pins are raised prior to the removal of the rails to keep them straight and ordered. After the rails are again inserted, the pins are lowered so that beat-up may occur. If the pins were not lowered, then the rails would not be able to slide to the side to make a space for the beat-up rod. The other feature evident in this drawing is a channel (C). This channel houses a lifter bar. The lifter bar is designed to lift one set of suspen-

sion bars a small amount, to remove the weight of the weaving array from the other set of suspension bars so that they may be removed more easily. For example, if the X direction rails are to be removed, the lifter bars beneath the Y rails would lift them 1/16". After the Y rails are lifted, there is no longer any contact between the top of the X rail and the weaving elements so that the X rail may now be removed and reinserted easily.

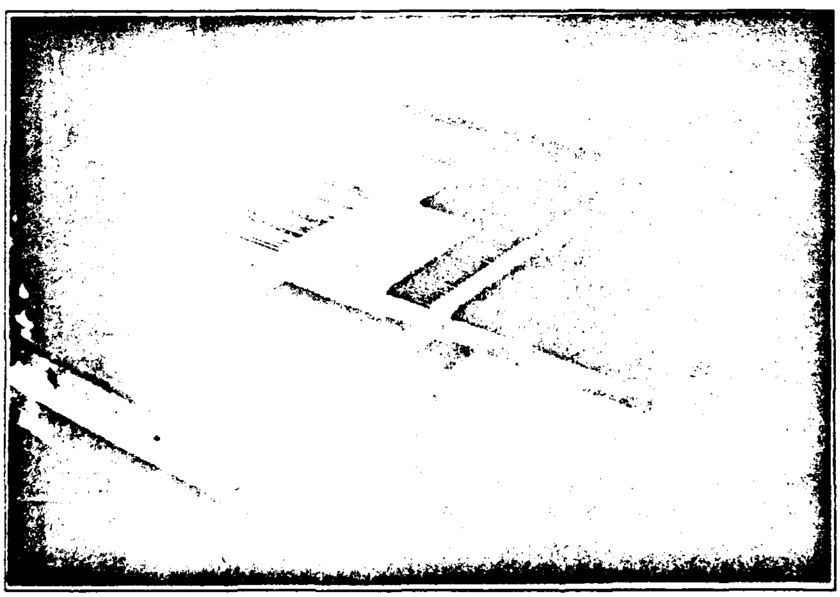
Following are some additional photographs of the SRWB with an array of elements in weaving motions:

X suspension rails as they are being removed from the element array.





Beat-up position , or filling insertion position between the X suspension rails.



Beat-up position or filling insertion position between the Y suspension rails.

FURTHER MODIFICATIONS NECESSARY TO VALIDATE SRWB

Unfortunately I was not able to correct all the specific problems associated with the manual SRWB within the timeframe of this SBIR program. It is probably not reasonable to expect that all phases of a research program go smoothly the first time, and designing and building this device proved to be a bigger job than I had anticipated at the onset of the program. Further modifications necessary to make the SRWB operational include:

1.) Resize the suspension rails
2.) Chamfer the edges of the weaving elements
3.) Implement the raising system
4.) Install the spacer/guide pin system

Modifications 1,2, and 3 are related, so they will be addressed together. After receiving the initial proof weaving elements from the injection molder, it was necessary to choose the exact dimension of the suspension rails. There were several factors influencing this decision:

- The slots in the elements which were to fit the rails were not exactly 1/8" (.125"), rather they measured .123 at the top and bottom of the slot due to shrinkage during cooling.

- The walls of the slots were not exactly horizontal, rather they bowed in slightly in the center.

- The elements seemed to slide easily on an undersized rail even when pressure was exerted on them, so the need for the raising system to remove contact between the top of the rail and the elements was dismissed.

- Since the edges of the elements were sharper than originally envisioned, I felt that the elements had to be positioned on the rails with no horizontal play so that the edges of the elements would not hang up on each other during element transposition.

- There was concern about the elements tilting on the bars as the fabric formation point got close to the weaving array, due to the outward component of the tension force applied by the elastic member (described in an earlier section). Due to this concern, the vertical dimension of the suspension rails was changed from 3/4" - which allowed for the raising system - to 7/8", which filled the entire length of the slot, and would not allow tilting to occur.

As a result of the above factors, the cross-sectional dimension chosen for the suspension rails was .118" thick x .875" tall. At the thickness of .118", the elements slid relatively easily, but the bowing at the center of the slot acted as a pressure spring and held then snugly without transverse play. I thought that this attribute would work to our advantage. Since the rails needed to be custom ground to this size, and lead time on this item was 6 weeks, I ordered the complete set instead of a small sample

quantity for a trial. The rails were ordered from the Starret Co., who make precision ground tool steel. The local grinders I checked with all said that they would not be able to maintain flatness of the rails if they were to grind standard stock to the required dimension. Starrett, who specializes in ground stock was able to assure flatness, but they would not make a special run for just a few pieces, so I would not have been able to get a trial quantity even if the long lead time were acceptable.

After receiving the rails, I found that the tall dimension was .005" too big, although this was within Starrett's standard specification on this type of ground product (the thickness was right on at .118"!). The rails were then ground from .879" tall to .875" at a local grinding outfit equipped with a Blanchard grinder. The elements now slid quite readily on the rails with just a slight friction. Unfortunately, this friction build up quite rapidly as the number of elements on the rail are increased. This build up of friction, combined with interference when both the top and bottom rails (X and Y rails) are in the element, made it quite impossible to remove the rails for weaving.

It is now clear that the elements must fit loosely on the rails in order for rail removal and insertion, motions central to the weaving process. I will get a new set of rails in the near future with a thickness of 7/64" (.109"). This causes another problem, hang-up of the edges of weaving elements during transposition. In order to eliminate this problem, we will need to chamfer all four longitudinal edges of the weaving elements. The amount of chamfer must be greater than the amount of transverse play between the rails and the elements in order to eliminate the possibility of hang-up. To chamfer the edges of the parts to the required depth of .010", I will build a holding fixture that will allow the edges to be shaved off with a razor blade. For additional molded weaving elements, the mold will have to be modified to reflect this design change.

Since the elements need to fit on the rail loosely, the tall dimension of the new rails will once again be the 3/4" originally planned. With the 3/4" rails, we can implement the raising system described before and reduce the friction resulting from moving the rails even further.

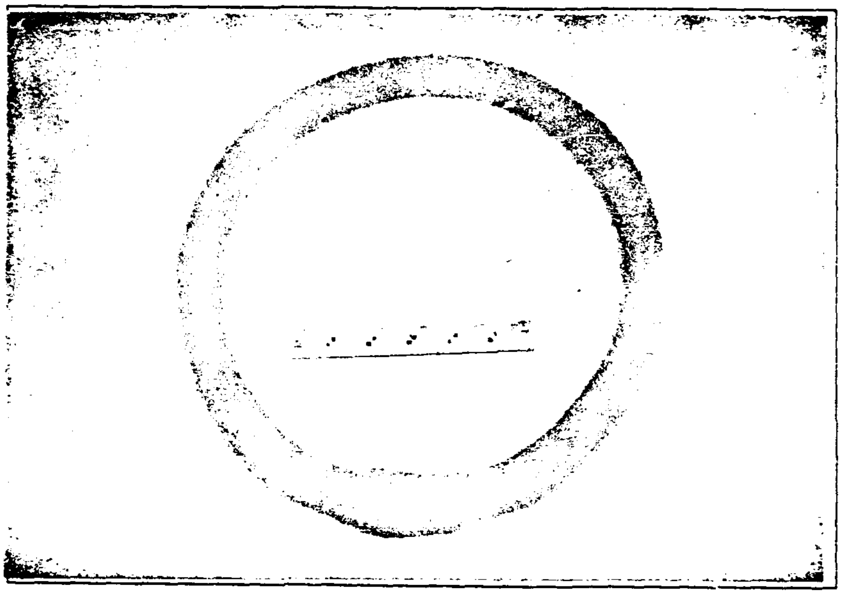
The spacer/guide pin system serves two functions. First it acts as a guide to keep the rails aligned as they are being removed from the array. Secondly they will keep the elements steady and in place as the rails of the other direction are being removed. This guide pin system was not installed during the course of this program:

- because installing it is a time-consuming operation
- weaving is possible - although somewhat slower - without it
- manufacture of the frame took significantly longer than expected and I was trying to finish only the necessary parts so that the program would finish on time.

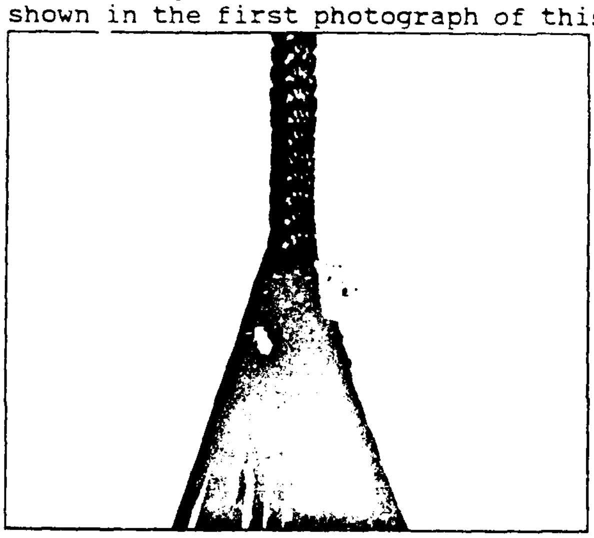
FABRICATION OF 3-D PREFORMS

Two 3-D preforms were fabricated as part of this program. These include:

1. 3-D Braided Ring with a Pleated Joint
2. Turbine Blade Preform demonstrating Hybrid Fiber Architecture

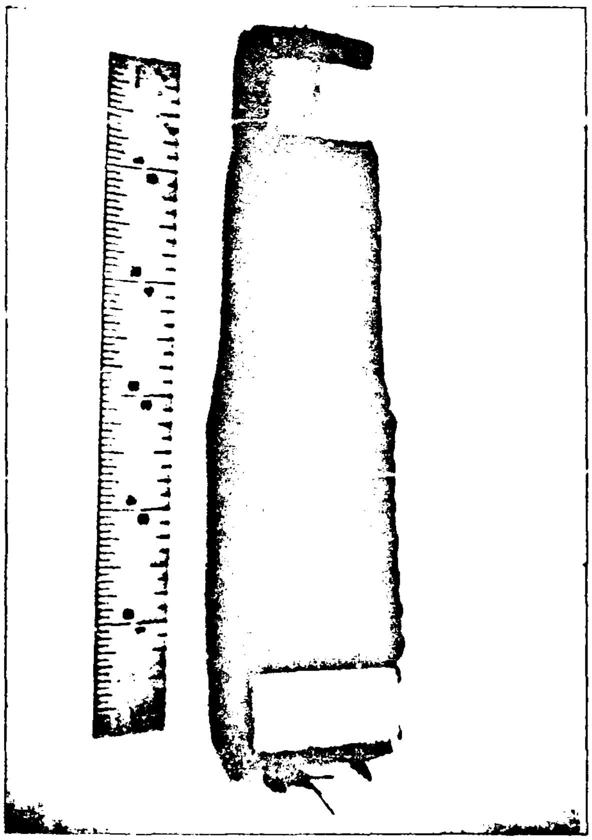


1. The photograph to the right shows a continuous 3-D braided ring joined at the bottom of the photograph with a pleated joint described in "MARFS Technology". The body of the ring is a 1,1 3-D braid made on a 10 x 10 weaving array, with 2 ends of Amoco T-300 12K carbon tow per weaving element. The machine used to make this part is the one shown in the first photograph of this paper. At both the beginning and end of the preform a 2" pleated section was woven into the structure, with a 34" length of the braid described above in the middle. The photograph on the left shows the lower pleated section before the preform was removed from the loom. After the preform was removed from the loom, the ends of the pleated section where the excess tows are cut were treated with a 10% solution of a high temperature epoxy resin dissolved in MEK. This MEK/Epoxy solution works very nicely as a binder, and keeps the ends from unravelling during the joining procedure. The pleats from



both ends were passed through each other to form the joint which was fastened with 2 rows of carbon fiber stitching with stitches at approximately every 3/16". The stitching was done with a latch needle common to the knitting industry using a looped stitch similar to a single thread chain stitch. Using this stitch, the equivalent of two 12K tows is left in the structure, perpendicular to the pleats, at each stitch location. The pleat at the bottom of the preform was slightly wider than the pleat at the top due to the outward component of the tension force described in Advantages of SRWB Technology (5.). If this structure would have been woven on the Suspended Rail Weaver/Braider, the pleats would have been more uniform.

2. The second preform fabricated was a "Turbine Blade" demonstrator woven on the 250 element prototype SRWB. I had hoped that the new weaver would have been ready to be able to fabricate an actual size turbine blade preform, but since this was not the case, the concept behind weaving this preform was demonstrated. This preform was fabricated with 240 ends of Amoco 12K Carbon tow, 1 end per element. The root section which would be attached to the hub of a rotating structure is a 1,1,1 orthogonal woven structure. This structure would have isotropic properties to withstand the complex loading present at the attachment point. The upper fiber architecture is a 3-D Braid with predominantly longitudinal tows to maximize performance in centrifugal loading at the tip of the blade. Depending on the needs of the designer, the structure of the blade could be an airfoil shape, contain 0° tows, and possibly be tapered by dropping tows toward the tip of the structure. Likewise, the architecture of the base can be tailored to suit the attachment mechanism.



BUILDING AN AUTOMATED 3-D WEAVER/BRAIDER

Figure 2 on the next page shows the basic schematic of an automated machine which would be able to produce continuous lengths of 3-D braided or orthogonal woven fabrics. The major components of this device are:

1. Fiber Supply Creel (34)
2. Weaving/Braiding Plane (22)
3. Compaction/Filling Insertion Combs (68)

The heart of this device is the weaving/braiding plane which consists of an array of miniature weaving elements, each of which contains a hole down the center to accommodate a fiber bundle. These miniature weaving/braiding elements are like the needle of a sewing machine or the latch hook of a knitting machine in that they approach the size of the yarn or fiber bundle that they are handling, and the total size of this miniature array approaches the size of the finished preform. The purpose of this plane(22) is to reduce the size of the 3-D array, or focus the yarns from the fiber supply plane, to the point that compaction of the interlacings may occur using small beat-up combs(68), blade like elements analogous to the reed of a conventional loom. Each of these blade like elements also has a channel which feeds an additional tow to the nose of the part. As the elements reciprocate to compact the interlacing formed prior to their actuation, they can also insert a filling yarn into the structure through this channel, greatly increasing the types of fiber architecture the device is capable of producing.

The way that this device operates is that each element or carrier in the fiber supply plane has a corresponding element in the weaving braiding plane. Both the carriers and their corresponding weaving plane elements make the same movements with respect to the cartesian array. For example, if the first X row in the fiber supply plane is moved one element to the left, then the first X row in the weaving plane is also moved one row to the left. As a result, no interlacings are formed between the fiber creel containing the carriers and the weaving/braiding plane containing the weaving elements. Since the preform or fabric is stationary, interlacings are formed only between the weaving/braiding plane and the fabric. After a group of interlacings has been formed, the beat-up comb is actuated, moves through the array of tows, engages the interlacings and pushes them to the fabric formation point. The density or "tightness" of the weave pattern is determined by the rate that the take-up device (80) draws the material away.

Fiber Supply Plane

The key to building an automated machine capable of producing a wide range of fiber architectures is in the design of the weaving/braiding plane and the beat-up combs. Building a fiber supply plane is a relatively straightforward task, and several companies have already demonstrated large cartesian arrays capable of making

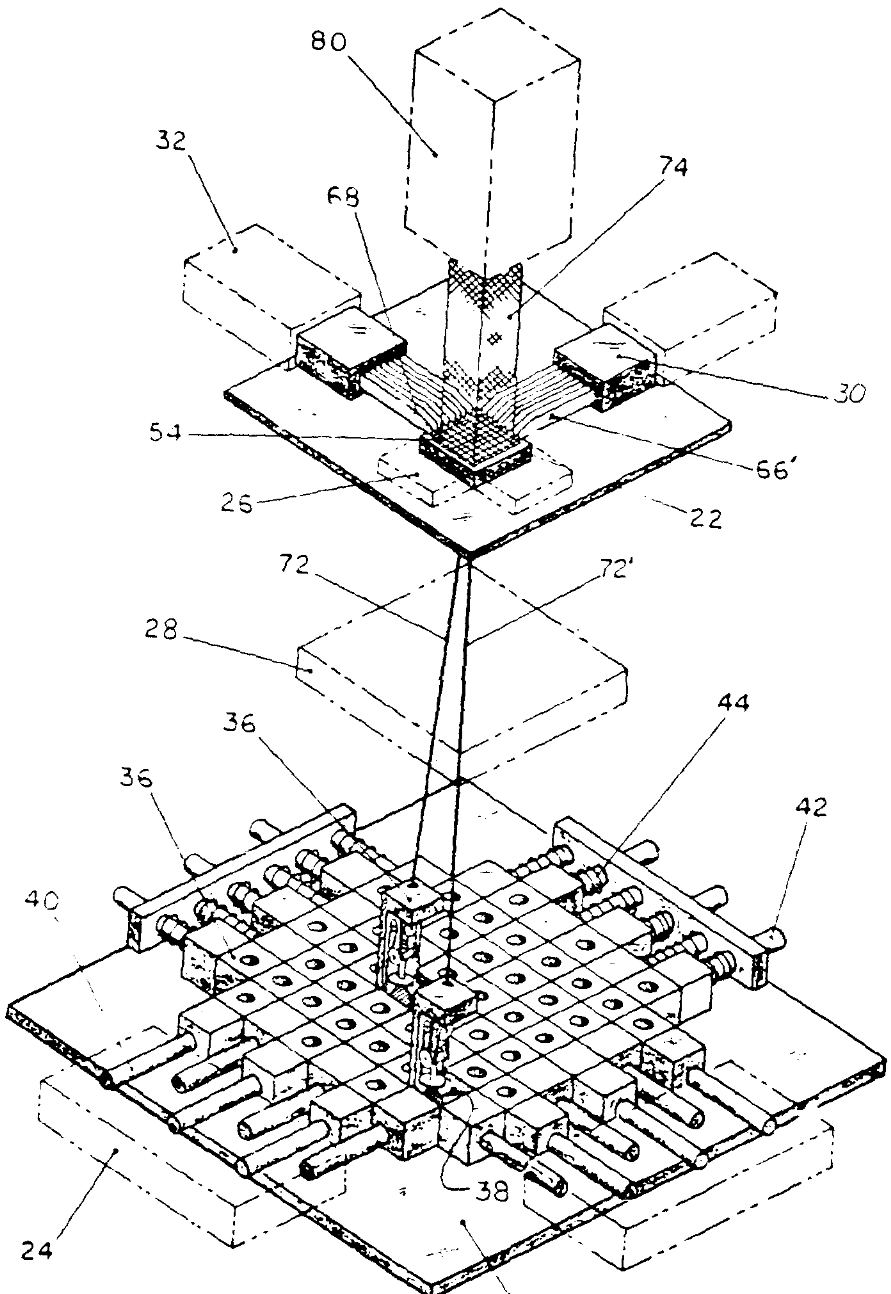
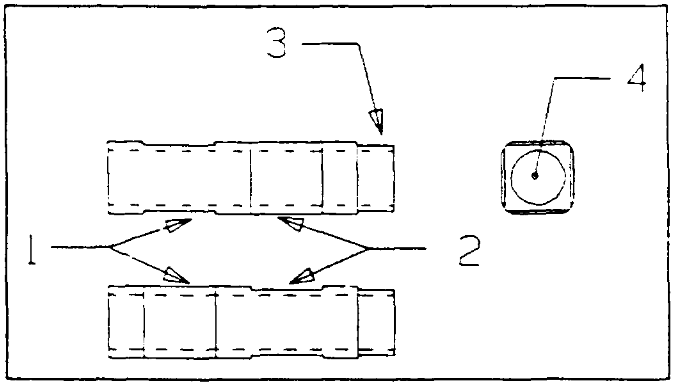


FIG. 2

the moves necessary to form 3-D braids. Automatic fiber compaction has been the stumbling block to automated 3-D braiding.
AB Carter, a company that has been making knotters and other mill devices for over 60 years has designed a braiding carrier with a compact design and the ability to take back long lengths of yarn. This ability to pay off yarn and then take back slack is important, because the longer the yarn that can be taken back, the larger a fiber supply array it is possible to set out. Also, the larger the fiber supply package, the more yarn it is able to hold so that longer lengths of preform are possible. These carriers would be ideal for holding yarns in the fiber supply plane, and AB Carter will soon have these carriers available at a cost of around $40/Carrier.

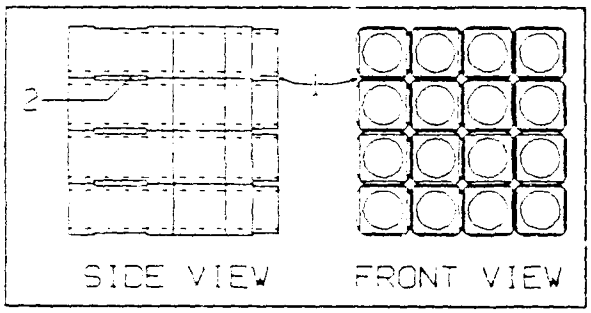
Weaving/Braiding Elements

In order to build a weaving/braiding plane of any usable size, it will not be possible in the vertical position shown in Fig.2, rather the machine will have to be horizontally oriented with the fibers parallel with the floor. In a vertical machine there must be provisions either built into the weaving elements, or spanning through the elements to support them during weaving. Given the space limitations between elements, it would be difficult to incorporate supporting means which would be strong enough or stiff enough to support the weight of a large weaving array, and the center of the weaving array would bend downward under its own weight, making element transposition very difficult. When the machine is in the horizontal position the weaving/braiding elements are able to sit on top of each other and the array will support itself. The tolerances of the elements will be very critical and they will have to be fabricated out of tool steel. These elements will be much too heavy to support in a vertical configuration, especially as larger arrays are attempted to be built.



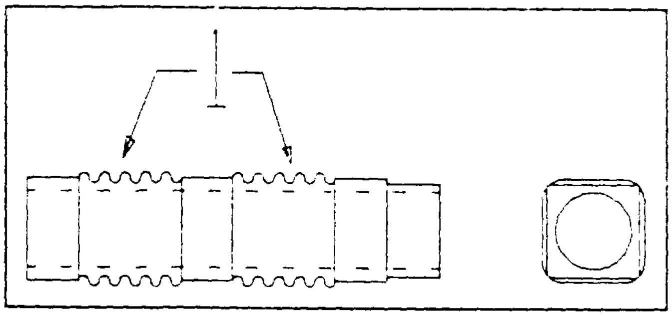
To the right is a diagram for one possible design of a weaving/braiding element for an automated 3-D weaver. The longitudinal edges of this device are well rounded to eliminate the possibility of element jamming during weaving due to edges catching on each other. The slots (1,2) which are oriented vertically and horizontally at the aft end of the elements are to accommodate guide rails which define the path of the elements. When the elements are to be moved horizontally, the vertical guide rails (2) are removed from the array to permit horizontal motion. When the elements are to be

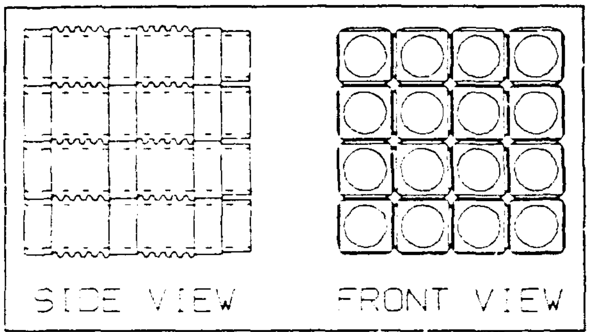
moved vertically, the horizontal rails (1) are removed. The notches in the front end of the elements (3) are for the beater combs. The sloped nose of the beater combs must enter the shed of tows below the top of the element, otherwise the risk of getting fibers caught between the bottom of the combs and top of the elements would exist. Also, this channel between the elements guides the combs as they move through the shed, and significantly increases the manufacturability of the combs allowing the use of flexible materials. The hole through the center of the weaving/braiding element (4) is where the fiber bundle or tow passes through. In order to get the maximum performance from an automated machine, the size of this hole must be tailored to a particular tow size. If smaller tows are to be used, the hole will have to be made smaller to reduce the overall size of the array, because the closer to the size of the fabric that the array is, the simpler the design and smaller the beat-up combs can be.



The figure to the left shows a front and side view of an array of elements. The channels which are to accommodate the beater combs (1) are clearly defined as the elements are stacked. (2) shows the channel in which the removable guide rails reciprocate.

Another possible design for weaving/braiding elements is to the right. With this design, guide rails are not necessary because the profiles (1) cut into the elements serve to guide the elements. These elements would be more expensive to make, but my feeling is that they might be more cost effective in the long run because of the elimination of a guide rail system. These elements could not be cut using conventional machining techniques. It would be feasible to fabricate them using Wire EDM technology.

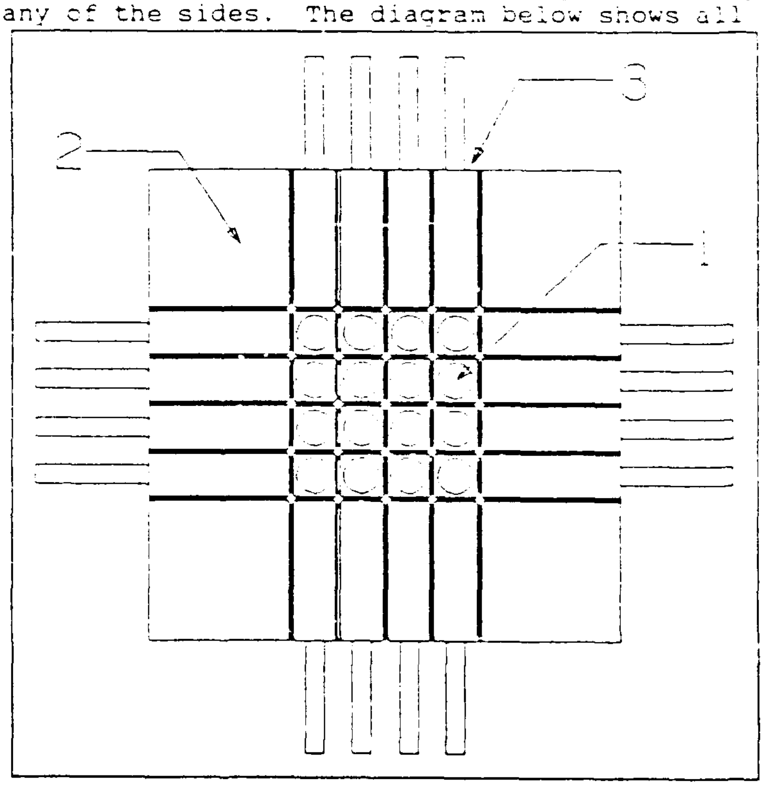




The diagram to the left shows a stack of elements with the serpentine profile. Note that the front end of the elements which are to accommodate the beat-up combs are the same in either element design.

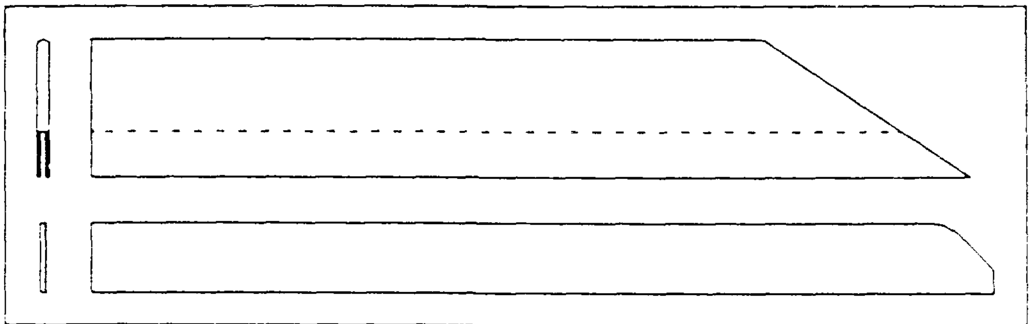
Floating Former Plate

The floating former plate is the assembly which forms the weaving/braiding plane. It was named the floating former plate because all the elements can "float" throughout this plane - they are not attached to any of the sides. The diagram below shows all of the elements in the former plate. These include the weaving/braiding elements (1), the corner blocks (2) which are stationary, and the actuator blocks with actuator rods (3). Not shown is an actuator system which should be capable of individually selecting rows for maximum freedom of fiber architecture. Also not shown is the frame which would house these elements. The diagram shows the elements in their neutral position, during weaving/braiding the elements must slide beyond this neutral position defined by the edges of the corner block, therefore each of the elements including the actuator blocks and the corner blocks must have profiles which match those of the elements cut into their sides.

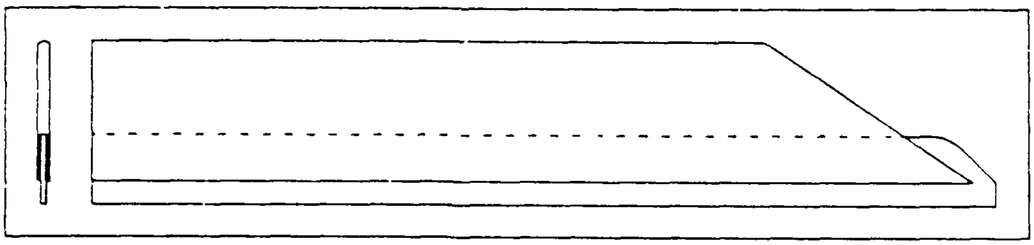


Beat-up Combs

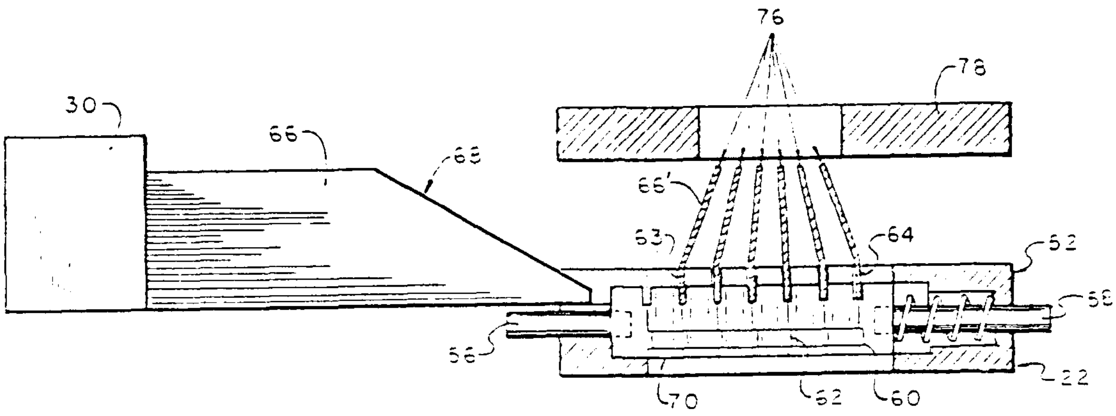
The beat-up combs are reciprocating elements that move through the shed, the space between the top of the floating former plate and the fabric formation point. The purpose of these elements is to engage the interlacings which are formed through element transposition and move them or "beat them up" to the fabric formation point. These elements will be comprised of 2 parts:



The lower portion of the comb will be made of a length of hardened spring steel, the same type of material that a hacksaw blade is made of. This part of the comb will travel in the channels formed between the top notches of the weaving/braiding elements. The upper portion of the element will be made of a second material, probably a semi-hard plastic which has the ability to bend a small amount laterally.



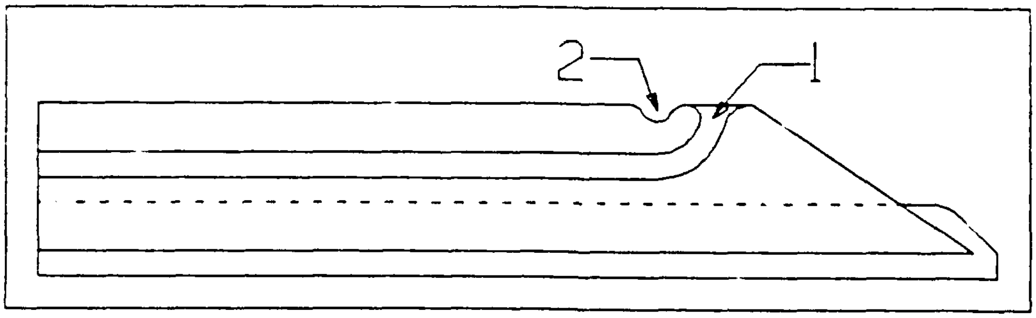
The upper and lower portions of the combs are bonded together to form the assembly. The reason that the combs need to bend laterally is shown in the diagram on the top of the next page. This diagram shows the floating former plate (22), a side view of the X beat-up comb (66), and a cross section of the Y beat-up combs (66'). Even though the weaving elements approach the size of the final fabric or preform, they will never be quite as small, which means that the tows at the outer edges of the weaving array will angle towards the formation point at a slight angle. The combs need to accommodate this angle either by bending during compaction, or by having this angle preset into the individual combs (76). When the design is validated in a demonstration loom, there will probably need to be both forms of comb deflection, because the cross sectional shape of the preform will change for shaping applications.



Beat-up Combs with Filling Insertion Capability

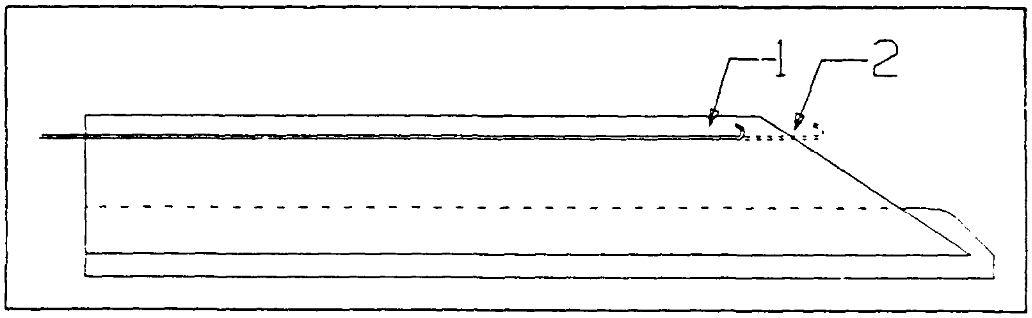
The next step after validating the design of the beat-up combs is to add filling insertion capability. Filling insertion capability will significantly increase the fiber architectures which may be formed. Without filling insertion, the machine would only be an automatic 3-D braider; with filling insertion capability it would be able to make all the various architectures described in the previous section on MARFS technology.

The easiest way to add this capability would be to put a channel into the beat-up comb to accommodate a filling yarn. The diagram below shows a beater comb with a channel (1) which is to accommodate a filling tow. The notch in the comb (2) is for a looper device which catches the filling yarn after the comb has moved through the shed. In this way, a filling yarn is inserted as the comb moves forward, and a second ply of yarn is inserted as the comb moves back. If a 1,1,1 orthogonal fabric is to be made, the filling yarns must be half the size of a warp yarn.



A second option in the design of a beat-up comb with filling insertion capability is to include a hook (1), similar to a compound latch needle used on a knitting machine, embedded in the body of the comb. The diagram on the top of the next page depicts such a comb. After the comb has moved through the shed, the needle is pushed forward (2) to receive a yarn. After the yarn has been

placed in the hook of the needle, the beater comb retracts through the shed, pulling with it the filling yarn. Using this method, two filling yarns are also being inserted in a single course, because essentially a long loop of yarn is being pulled through the shed to form the filling insertion.



Before a design for the beat-up combs can be finalized, materials that will work for the application must be selected. The design of the filling capable combs will depend on what kinds of shapes can be fabricated from these materials.

Automated 3-D Weaver/Braider Summary

There is still a great deal of development work necessary before it is possible to build an automated 3-D weaver/braider capable of producing the wide range of fiber architectures, and hybrid architectures described in this report. The most cost effective way to work towards the goal of eventually building a full scale automated device is to validate the components involved with this technology. The first step is to build a small automated 3-D braider based on the floating former plate/beat-up comb technology outlined in this section. After the braider is operational, then the filling insertion capability should be added to the device. It is not until the technology has been proven feasible through such an effort that a full scale 3-D machine should be attempted.

APPLICATIONS FOR 3-D HYBRID FIBER ARCHITECTURES

Having been in touch with several of the turbine engine manufacturers and high temperature composites manufacturers, it is quite evident that there is a high interest in 3-D reinforced structures for high temperature materials applications. The companies that have been contacted include:

Engine Manufacturers
- General Electric, Cincinnati
- Pratt & Whitney, West Palm Beach
- Teledyne CAE Turbine Engines, Toledo
- Williams International, Walled Lake

High Temperature Composites Manufacturers
- RCI, Whittier
- Ultramet, Pacoima
- Amercom, Chatsworth
- FMI, Biddeford
- Textron, Lowell

Among the engine manufacturers there is an universal interest in 3-D reinforced structures because these structures will help them develop the materials which will allow them to design and produce the next generation of turbine engines. The applications for 3-D structures suitable to MARFS technology that get talked about time and again include:

- Inlet nozzle vanes
- Turbine rotors
- Ring structures
- Actuators and shafts with transitions to attachment points

After having been in contact with the companies above it is clear that development programs relating to MARFS technology must be coordinated through the engine manufacturers. During the period of this program, I was not able to schedule personal visits with the turbine engine manufacturers which I plan to do over the next few months. It will take a more thorough marketing effort to clearly define the application possibilities and requirements relating to the 3-D technology that have been developed by ITAC.

CONCLUSION

3-D preform technology will be critical to the development of advanced high temperature material systems. This technology will complement new developments in fiber systems, fiber coatings, and matrix systems. It is only through the integration of all these disciplines that cost effective solutions to the material challenges facing the propulsion industry will be created.

The USAF DoD /NASA IHPTET program is a classic example of how this integration will be necessary to meet the goals of the program. Even if fiber/matrix systems which meet the temperature requirements are developed, there must still be cost effective preform manufacturing technology in place to maximize the performance of these fiber/matrix systems. This preform fabrication technology will need to provide shaping capability, control over the fiber architecture, achieve high fiber volumes, and be able to produce preforms repetitively at reasonable cost.

There is no doubt that classic textile fabrication technology including weaving and braiding will play an important role in the development of certain components. For more complex, thicker components such as turbine blades and ring structures, new technologies must be developed which do not demand the compromises in fiber volume or translational efficiency evidenced when applying conventional textile technology to these applications.

ITAC/Western Filament is uniquely suited to the further development of innovative 3-D preform structures because:

1. We have experience with conventional textiles, and are aware of both their capabilities and limitations. We can draw from conventional technology where applicable.

2. We have shown that new versatile fiber architectures can be designed and fabricated.

3. We have identified and defined areas for development which will lead to the fabrication of automated equipment capable of producing these versatile 3-D fiber architectures.

In the next few months, the Suspended Rail 3-D Weaver/Braider will be finished and operational. We will fabricate samples of airfoil shaped turbine engine blades with hybrid root structure, examples of tubes with transitions to solid attachment points, and further refine pleated jointing techniques. We will also initiate a marketing effort to identify both partners and applications for further preform development efforts.

ITAC/Western Filament is an excellent candidate for a Phase II follow on effort to this program because we have the technology to concurrently produce prototype preforms to validate component designs and fiber/matrix systems, while developing the automated 3-D weaving/braiding technology necessary for the high volume fabrication of these preforms.

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